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A STUDY OF THE MHD INSTALLATION U-02 DURING PROLONGED OPERATION

V. A. Kirillin, A. Ye. Sheyndlin, B. Ya. Shumyatskiy, V. V. Kirillov, D. A. Vysotskiy, D. K. Burenkov, S. I. Pishchikov, P. G. Poletavkin, I. A. Mostinskiy, V. I. Sukhov, and L. V. Krauze

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A STUDY OF THE MHD INSTALLATION U-02 WITH ITS OPERATION UNDER LONG-TERM CONDITIONS

V. A. Kirillin, A. Ye. Sheyndlin, B. Ya. Shumyatskiy, V. V. Kirillov, D. A. Vysotskiy, D. K. Burenkov, S. I. Pishchikov, P. G. Poletavkin, I. A. Mostinskiy, V. I. Sukhov, and L. V. Krauze

ABSTRACT. The main results of experimental studies obtained in 1965 - 1971 on the mock-up power installation U-02 with a MHD generator are presented. The U-02 installation, being an assembly, enables one to conduct long-term tests of models of the entire power equipment complex of prospective MHD stations. A high-temperature air heater was worked out in the U-02 installation and long-term operational tests (around 10,000 hours) were conducted. The possibility was demonstrated of the stable heating of air in this unit to 1,500 - 2,000° C. The distinctive features of the operation of various versions of combustion chambers for MHD installations were studied. An inlet system and three variants of the outlet system of the admixture were tested. The behaviour of the admixture in the installation loop was investigated, particularly in the model steam generator. A multielement inverter facility using silicon thyristors was developed and tests were conducted. The inverter provides for the removal of power from the MHD generator and the delivery of the power to a power supply line. Major consideration was given to the results of investigating the characteristics of a MHD generator and the behaviour of "cold" and "hot" structures of the MHD channel during its long-term operation. The "hot" construction of the channel with ceramic electrodes and modular walls, which was recently developed, enable one to increase the power of the MHD generator up to 75 kW with a specific removal up to 3.3 MW/m^3. Long-term tests of such a design have demonstrated the high stability of its electric characteristics.

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INTRODUCTION

The U-02 installation which was placed into operation more than five /3
years ago remains up to now the only prolonged operating mock-up MHD installation in the world having all the basic elements of future power stations using a MHD generator. These elements (Figure 1) are the compressor group, high-temperature air heater, oxygen enrichment system, combustion chamber, admixture inlet and outlet systems, MHD channel with electromagnet and load arrangement, steam generator, following heat exchangers and, finally, an exhaust group after which the combustion products are ejected into the atmosphere through an exhaust duct. The initial arrangement of the installation which is described in [1] was substantially improved. The purpose of the improvements was to make the operating conditions of the U-02 equipment elements approximate the conditions of prospective power installations using a MHD generator, and also /4
to test and finalize the models of the units of the first of such installations — the U-25 [2]. While conducting the tests, the test conditions of the remaining elements must be ensured for each of the U-02 installation elements. Despite the attempt to make maximum use of commercially manufactured industrial equipment, we nevertheless were obliged to manufacture the majority of the installation's units from scratch.

During the operation the main parameters of the flow, that is the temperature and pressure (see Table 1), were significantly increased, and the compressor group at the installation's intake was reinforced, enabling the retardation pressure at the U-02 loop intake to be raised to 1.7 atm.

A high-temperature air heater (HTAH) was developed for heating the air to 1,500 - 2,000° C [3]. The combustion chamber and air duct of the hot air blower were replaced. This was due to the increase of the air temperature. An oxygen system operating from supplied tanks of liquid oxygen with a capacity of 2 x 6 T and a liquid fuel supply system were introduced into the arrangement. A multielement inverter facility using silicon rectifiers was

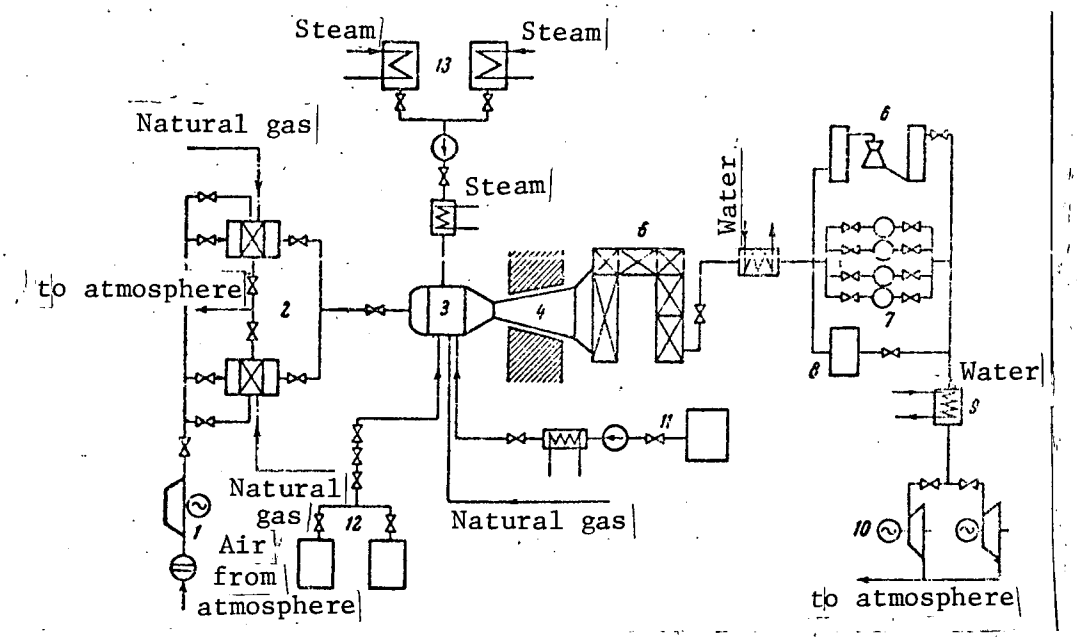


Figure 1. Schematic diagram of the U-02 installation: 1 - gas blower, 2 - high-temperature air heater, 3 - combustion chamber, 4 - MHD generator, 5 - model steam generator, 6 - wet admixture outlet system, 7 - dry admixture outlet system, 8 - experimental electric precipitator, 9 - heat exchanger, 10 - vacuum pumps, 11 - liquid fuel supply system, 12 - oxygen supply system, 13 - admixture supply system.

established allowing the power of the MHD generator to be delivered to the Mosenergo (Moscow Power System) power supply line.

The main changes introduced into the thermal loop of the U-02 installation were described in [4].

TABLE I

MAIN CHARACTERISTICS OF THE U-02 INSTALLATION

Flow rate, kg/sec	
combustion products	1.50
oxygen	0.35
fuel	0.12
including:	
gas	0.10
petroleum residue	0.02
Degree of oxidant enrichment with oxygen, %	up to 50
Temperature of the oxidant heating, °C	1,500 - 2,000
Maximum pressure beyond the compressor group, absolute atmospheres (atm)	1.5 - 1.7
Adiabatic temperature in the combustion chamber, °C	2,650
Temperature at the channel intake (measured), °C	2,500
Retardation pressure at the channel intake, atm	1.3
Retardation pressure at the channel outlet, atm	0.4
Velocity of the channel, m/sec	700 - 900
Mach number	0.6 - 0.85
Consumption of admixture solution, g/sec	50

HIGH-TEMPERATURE AIR HEATER

The successful solution of the problem of creating high-power electric /6
power stations with an open-cycle MHD generator is determined to a considerable extent by the possibility of heating air to temperatures of 1,500 - 2,000°C. At present, the highest level of air heating (1,100 - 1,200°C) is achieved in metallurgy.

In order to study the problem of heating air to higher temperatures, an experimental high-temperature air heater — a two-chamber regenerative heat exchanger with a fixed spherical packing and a valve gas distributor — was established in the installation in 1965 - 1967. The air heating is achieved by means of the heat of combustion products obtained in the internal combustion chambers of the regenerator [1, 3]. The heat exchanger is designed for heating the air to 1,500 - 2,000°C. An air heating level of 1,500 - 1,700°C was achieved already in 1968 after careful adjustment. Since then, the air heater has operated in the loop of the U-02 installation upwards of 10,000 hours, providing stable heating of the air to these temperatures with gas consumption rates up to 1.2 kg/sec [5]. Evidently this was the first time such a long operating time for a heat exchanger was achieved with the heating of air to the indicated temperatures.

In two runs of the heat exchanger, using packing made of zirconium dioxide, an air temperature of 1,800 - 2,040°C was consistently obtained for a period of around 50 hours. In these runs a bypass air pipe was used to heat part of the heated air for compressing the fuel and for obtaining gas temperatures of 1,900 - 2,160°C in the internal combustion chambers of the heat exchanger.

Thus, the possibility of obtaining the designed temperatures of air heating in a heat exchanger of the given design was experimentally verified.

In order to evaluate the operating effectiveness of the spherical packing and the efficiency of the refractory materials being used at high temperatures, the temperature conditions of the packing and stack as well as the heat transfer and hydraulic resistance in the spherical packing layer were studied, and also regular observations were made of the condition of /7 the packing and stack. The studies were conducted with flow rates of the heated air and combustion products of 0.4 - 1.2 kg/sec, pressures of 1.2 - 1.4 atm, air heating temperatures of 400 - 1,700°C and regenerator operating cycle times of 6 - 18 min. The temperature of the gas medium and the spheres, which was measured by thermocouples and optical pyrometers in five cross sections of the packing layer, was recorded by means of electronic potentiometers. Figure 2 presents a characteristic graph of the temperature change in one of the cross sections of the layer during a cycle of the regenerator's operation.

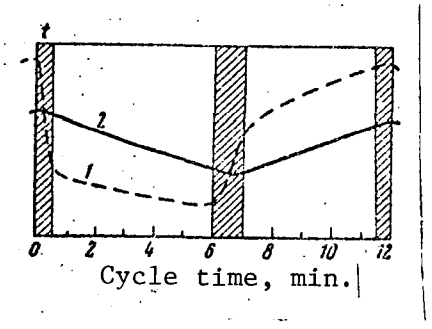


Figure 2. Temperature changes of the gas medium and spheres during a cycle of the regenerator's operation with the ratio of the water equivalents of the air being heated and the combustion products equal to one:
1 - temperature of the gas medium
2 - temperature of the spheres.

The temperature conditions of the spherical packing depend in a substantial way on the ratio of the water equivalents of the air and combustion products. The ratio of the water equivalents of the heat transfer agents equal to or close to one is the optimum ratio. In this case the distribution of the temperatures of the air, spheres and combustion products has practically a linear character (Figure 3), and the temperature heads and temperature fluctuations in all the cross sections of the layer are the same. The thermal load is distributed uniformly along the layer and the entire packing volume participates with equal effectiveness in the heat exchange.

The ratio of the water equivalents of the heat transfer agents also proves to have a similar effect on the temperature fluctuations of the stack;

however, the amplitudes of the fluctuations in this case are smaller.

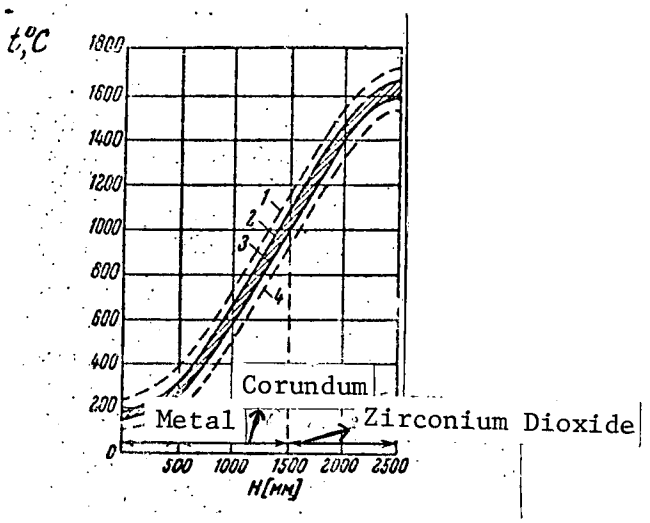


Figure 3. Profiles of the temperature distributions of the combustion products, spheres and heated air in the spherical packing layer with the ratio of the water equivalents of the heat transfer agents equal to one:
1 & 4 - average temperatures of the combustion products and air during a cycle of the regenerator operation,
2 & 3 - maximum (at the end of heating) and minimum (at the end of cooling) temperature of the spheres.

The experimental data concerning the heat transfer of the spherical packing under unsteady operating conditions were processed in the form of the relationship of the Nusselt and Reynolds numbers. The diameter of the spheres was taken as the controlling dimension. The Reynolds number was calculated on the basis of the relative flow velocity in the regenerator cross section which is free of packing. In the range of Reynolds number change from 200 to 1,200, the precise relationship $Nu = 0.19\ Re^{0.9}$ was obtained with an experimental scatter of $\pm$ 20%. This relationship agrees satisfactorily with the relationships obtained earlier at lower temperatures [6]. Because of the highly extended surface and high heat transfer coefficient, the spherical packing has a very high thermal efficiency. /8

When processing the experimental data on the hydraulic resistance of the spherical packing layer, the drag coefficient and Reynolds number were calculated on the basis of the actual velocity of the gases in the layer and an equivalent diameter, which is equal to four times the ratio of the layer's porosity to the specific surface of the packing. In this same range of Reynolds number changes, the following relationship of the layer's drag coefficient as a function of the Reynolds number was obtained (the scatter

of the experimental points was ± 10%):

$$\xi = 2.4\ Re^{-0.2}$$

The results obtained also agree satisfactorily with the data of reference [7]. Observations have shown that when heating the air to 1,500 - 1,700°C and with temperature fluctuations of the packing during the period of 50 - 150°C (when the rates of the temperature change of the spheres is 10 - 30°C per minute) a spherical packing made of zirconium dioxide and aluminum dioxide (corundum) operates entirely satisfactorily over a long period of time. Burning or local deformation at the contact spots was not detected nor was there any appreciable disintegration or cracking of the spheres. Spheres made of ShKh-15 ball-bearing steel which were located in the bottom low-temperature parts of the packing layer had a dark-dull color because of a coating of oxide film which protected them from subsequent corrosion. The condition of the stack made of fireclay, mullite-corundum, magnesite and zirconium dioxide was good after prolonged operation of the air heater under the most diverse conditions.

Measurements also have shown that because of good thermal insulation, /9
the heat losses in the heat exchange chambers, combustion chambers, the fork and tee of the regenerator are small. The main heat losses occur in the high-temperature valves which are water cooled. The reduction of the air temperature in the valves is inversely proportional to the air flow rate. With the nominal flow rate of 1 kg/sec, it is altogether only 30 - 40°C. With an increase of the output of the air heater, these heat losses will be still smaller.

The operational tests of the high-temperature regenerative air heater verified the reliability of the operation of the main units and systems, among them the distributor valves.

In the process of making operational tests and studies of the high-temperature air heater, experience was accumulated and data obtained which

are necessary for the design, construction and establishment of commercial equipment.

COMBUSTION CHAMBER

The creation of combustion chambers for MHD installations operating on gaseous fuel requires the development of schemes for the organization of combustion which ensure a high thermal efficiency, operating stability in a sufficiently broad range of change of the fuel and oxidizer parameters, and the possibility of even heating.

Studies were conducted over a number of years on the U-02 installation which now enable one to determine the practical upper limit for forcing, the most rational geometry and aerodynamic scheme of the combustion chamber.

The main direction in the investigations was the study of problems of ensuring stable, vibrationless combustion conditions.

The two schemes of the combustion chambers which were studied are presented in Figure 4. The presence of recirculation zones is a characteristic of the schemes. As the studies which were conducted showed, stable operation of the combustion chambers may be obtained when the value of a certain criterion M is larger than a critical value M_{cri}. The criterion M is the ratio of the kinetic energy of the stream flowing out of the burner to the kinetic energy of the recirculation vortex. With forcing, that is with a reduction of the dimensions of the combustion chamber, the condition $M_1 > M_{cri}$ must be strictly satisfied. The values of M_{cri} (see Figure 4) were experimentally determined on the U-02 installation for the different schemes. /10

Figure 5 presents the results of studies of the stable operating zones of a combustion chamber having an aerodynamic flow scheme (see Figure 4 variant "a"). From the graph it is seen that with an increase of the air temperature entering into the combustion, the zone of unstable operation

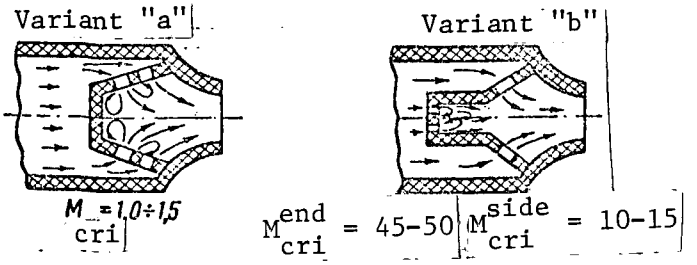


Figure 4. Schemes for the organization of the flow aerodynamics in combustion chambers.

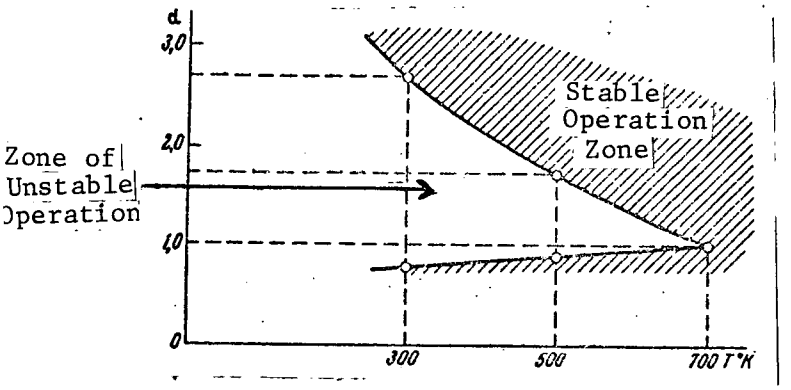


Figure 5. Change of the stable operating zone of a combustion chamber as a function of the excess factor and oxidant temperature.

contracts, and when a certain critical temperature of air heating is reached, the zone disappears in general.

The optimum thermal stress in the combustion chamber space for the U-02 installation, based on the conditions of smallest thermal losses and hydraulic resistance, is $1.5 \cdot 10^8 - 3 \cdot 10^8$ kcal/m^3 hr. However, since the ionizable admixture which is being supplied to the combustion chamber in the form of an aqueous solution must succeed in reaching thermodynamic equilibrium with the combustion products, one should reduce the magnitude of the thermal stress in this space to $0.7 \cdot 10^8 - 1.0 \cdot 10^8$ kcal/m^3 hr.

The schemes presented in Figure 4 also are very good from the point of view of reducing the thermal losses since a large part of the heat leaving the combustion zone is transmitted, through the body of the combustion device, to the air entering the combustion and again returns to the combustion chamber.

One should point out that the combination variant "b" (see Figure 4) enables one to achieve a rather smooth temperature increase of the combustion products because the cylindrical section in this case plays the role of a forechamber.

Altogether around ten combustion chamber variants were tested on the U-02 installation. Stable operation was achieved with a temperature of the combustion products up to 2,650°C. The duration of continuous operation at these temperatures was more than 1,000 hours. This duration was determined basically by the durability of the highly refractory material of the chamber's inner lining in the atmosphere of combustion products with the alkaline admixture. Tamped masses made on a base of either zirconium dioxide or aluminum oxide are used as these materials. These masses have operated satisfactorily at a temperature of 1,500 - 1,700°C. The experimental data obtained, with consideration of the distinctive features of the construction, of the preparation technology and a number of other factors, enable one to select variant "b" (Figure 4) as a promising scheme for high-power MHD installations. /11

The resulting data served as the basis for developing another combustion chamber variant for the installation U-25, the preparation of which will be completed in 1971.

PROBLEMS OF THE INLET AND OUTLET OF THE IONIZABLE ADMIXTURE

INLET AND IONIZATION OF THE ADMIXTURE

The ionizable admixture is introduced into the combustion chamber in the form of a 50% aqueous solution of K_2CO_3 or a 67% solution of Cs_2CO_3 and is sprayed by means of centrifugal nozzles. The process of the vaporization of the solution drops in the conditions of the combustion chamber is very complicated and does not yield to precise calculation. According to estimates, the time for vaporization of a drop with an initial diameter of 100 mm in combustion products at $t \approx 2{,}800°K$ is around 40 msec [8].

In order to study the ionization process, a special single-pass combustion chamber was developed, in which the admixture could remain for 15 msec. Ten holes were made along the length of the chamber for inserting probes. The

studies which were conducted showed that the electrical conductivity of the combustion products monotonically increases along the chamber, does not reach a stable level, and the admixture ionization zone also extends to the MHD channel. Now the question is posed as to how to obtain such a dispersion of the sprayed solution which would shorten the admixture vaporization and ionization time to 10 msec. In order to do this, it is necessary to obtain drops with a dimension of less than 50 micron. This may be done by increasing the spraying pressure to 500 kg/cm^2 and by reducing /12
the diameter of the outlet nozzle to 0.3 mm. But such a variant is difficult to achieve and has a low reliability. On the U-02 installation, other methods of spraying the solution were studied, in particular pneumatic nozzles and the introduction of a superheated solution under a high pressure. In the latter case, the boiling up of the solution associated with the drop of pressure at the moment of discharge from the nozzle leads to secondary breakdown of the drops. The tests of such a system gave faily good results.

BEHAVIOUR OF THE ADMIXTURE IN THE MHD CHANNEL

In the thermodynamic equilibrium conditions of the MHD channel, the admixture is found basically in the form of KOH, K and K^+. The ratio of the concentrations of these components is determined by the temperature [9]. Condensation of the KOH vapors occurs on the cold surfaces of the channel walls ($T_w \leq 1{,}100°K$) with subsequent conversion to solid K_2CO_3 (T_{melt} = 1,174°K). In this way, a solid layer is formed on the cold wall. Its thickness depends on the heat flux. A melt of a KOH-K_2CO_3 mixture moves along the surface of the layer, discharging to the exit cone and heat exchanger mounted beyond the MHD channel. An investigation of the KOH condensation process with a longitudinal streamline gas flow over the surface showed that the analogy between the heat exchange and the mass exchange is preserved here.

In long MHD channels with cooled walls, the thickness of the thermal boundary layer may be on the order of 10 cm. In order that the conversion of

KOH to K_2CO_3 and that subsequent volumetric condensation may take place, the time for the admixture to remain in this layer must be sufficiently long. Thus, a condensation aerosol may appear in the boundary layer. Its particles, under the action of diffusion and thermoforetic forces, precipitate on the cold surface.

In the case of MHD channels with hot ceramic electrodes and insulated walls (T_w > 1,500°K), carbon dioxide and KOH vapors penetrate into the ceramic. The KOH vapors condense in a zone where the temperature is low. The carbon dioxide enters into a reaction with the KOH, forming solid K_2CO_3. The ceramic is saturated by the admixture and its properties change. In order to avoid this phenomenon, it is necessary to increase the temperature of the ceramic to 2,000 - 2,100°K.

BEHAVIOUR OF THE ADMIXTURE IN THE MODEL STEAM GENERATOR

Experience has shown that the reliability and effectiveness of the operation of a model steam generator (MSG) basically are determined by the admixture deposits. In the high temperature zone of combustion products (above 1,500°K), KOH vapors condense on the tubes of the MSG, the same as in the MHD channel, with the formation of a solid crust of K_2CO_3 and a melt of a mixture of KOH with K_2CO_3 flows along the crust. The thickness of the crust in zones of reduced heat fluxes reaches several centimeters. To avoid clogging by the admixture, this part of the MSG — the ascending column — is made in the form of a radiation chamber with a volume of about 1 m^3 and with semiradiation baffle surfaces with a width of the gas passages of about 60 mm. Such a construction of the ascending column ensures its long operation without a change of the hydraulic resistance. However, the heat exchange characteristics noticeably deteriorate in proportion to the operation with the admixture: the average heat transfer coefficient gradually decreases, and after five or six hours it stabilizes at a level of 50% of the initial value.

A heat exchanger is used for cooling the combustion products after the

MHD generator. The heat exchanger is the model steam generator (MSG) and enables one to reproduce the operating conditions of the heat exchange surfaces in a flow of combustion products with admixtures which are characteristic for power station MHD installations.

The melt flowing along the radiation chamber walls is run off into a tank with water. In this way, up to 40% of the admixture introduced into the loop is recovered. Beyond the ascending column, the temperature of the combustion products is reduced so much that the carbonate K_2CO_3 is formed and bulk condensation begins. The diameter of the forming particles as measured by a FPS-2M light diffusion instrument was close to 0.2 μm. Falling in the MSG descending column, the particles settle on the surfaces of the tubes forming loose deposits, gradually (after 5 - 6 hours) closing over the gas passages. This leads to a sharp increase of the hydraulic resistance and to a deterioration of the heat transfer to approximately half its original value. Reliable cleaning of the tubes of the loose deposits is accomplished by periodically washing them with water for 5 - 10 minutes after each 5 - 6 hours. As a result, the hydraulic resistance decreases, and the heat transfer coefficient increases to the initial value.

ADMIXTURE OUTLET /14

Recovering the ionizable admixture from the departing gases may be achieved in either of two parallel outlet systems: "dry" (7) or "wet" (6) (see Figure 1).

The results of tests of the "dry" admixture outlet system were already discussed in [1]. The tests showed that operation of a large number of bag filters is difficult. Therefore, for the experimental-industrial U-25 installation, a "wet" admixture recovery system was selected [2]. The model of such a system, which was designed for a combustion product flow rate up to 2 kg/sec, was mounted on the U-02 and long-term tests were carried out. This system proved to be simple and reliable in operation. Moreover, during 2.5 years of its operation, not a single breakdown occurred.

The duration of the contact of the K_2CO_3 solution with the metal exceeded 20,000 hours; however, no noticeable formation of corrosion was detected. The system enables one to recover upwards of 99% of the admixture. However, its hydraulic resistance is appreciable when this is done. The results of the study of the "wet" admixture outlet system were discussed in detail in [10].

The complexity of operating the bag filters and the high hydraulic resistance of the "wet" recovery system compelled us to continue the search for the most favorable variants of the admixture outlet for future MHD power stations.

Tests of electric precipitators, both dry and also sprinkling, were conducted on the U-02 installation. The tests of the sprinkling electric precipitator designed for a flow rate of up to 200 g/sec gave satisfactory results. With a precipitator electrode length of 0.8 m, a gas velocity of 0.5 - 0.7 m/sec, and an operating voltage of around 50 kV, more than 95% effectiveness in removing submicron K_2CO_3 dust was obtained, which when converted to a four-pole industrial filter — corresponds to an efficiency of 99%.

INVERTER FACILITY

A multi-element inverter facility using silicon thyristors was produced, studied, and introduced into operation. The facility enables one to remove electric power from 40 independent electrode pairs of the MHD generator and to deliver it to an alternating current electric power system. The inverter had high reliability and good operational qualities [11]. Because of the /15
necessity of optimizing the electric load of the U-02 MHD generator, a special voltage regulator was developed. In order to bring the MHD generator to conditions of maximum electric power, the constant incoming information concerning the derived total power of the MHD generator on the basis of the voltage is used. When there is a simultaneous discrete voltage change ΔU on all the electrode pairs, a certain change of the power value ΔP occurs

because of a corresponding change of the triggering lead angle β of the rectifier converter bridges. The sign and magnitude of the change are uniquely related to the electric load factor. A search for the position at which $\Delta P/\Delta U = 0$ is used as the regulator operating point. The change of the total MHD generator power is produced on the primary side of the inverter transformer for the first harmonics of the current and voltage.

The operating cycle of the regulator consists of two cycles of the primary current. During the first cycle, the voltage on the electrodes has the value U_{e1}, and during the second cycle — $U_{e2} = U_{e1} \pm \Delta U_e$ (ΔU_e is the voltage increment).

A change of voltage increment sign occurs when, during the second cycle, a decrease of the power in comparison with the first cycle occurs, which means the introduced voltage change is unfavorable from the point of view of approaching the power maximum. Close to the power characteristic maximum, a continuous change of the sign of ΔU_e occurs after every two cycles of the line voltage. Positive and negative voltage increments are 1 - 2% of the average value. Thus, an additional alternating component appears on the voltage of the electrodes with a frequency of 25 hertz and an amplitude not exceeding 1% of the average value of this voltage. The corresponding power fluctuations are quite insignificant, since they are proportional to the square of the relative voltage change.

When conducting the experiments, the automatic electric load stabilizer ensured operation of the MHD generator under maximum power removal conditions with an electric load factor of $\eta_e^{av} \simeq 0.5$. In order to obtain other values of the electric load factor, it is necessary to introduce different-phase filtration of the voltage and current measured on the primary side of the inverter transformer [11]. /16

Figures 6,a and 6,b present curves of the distribution of η_e along the channel and an oscillogram of the transient process of the U-02 MHD generator under conditions of maximum electric power.

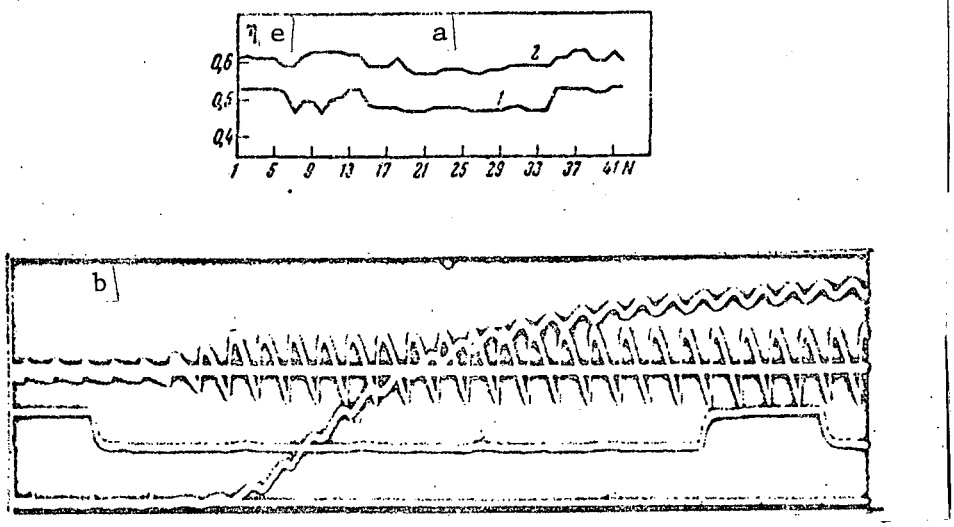


Figure 6. Distribution of the electric load factor along the channel (a) and arrival at conditions of maximum power (b):

a) 1 - $\eta_e^{av} = 0.5$; 2 - $\eta_e^{av} = 0.6$;

b) 1 - average values, 2 - instantaneous value, 3 - signal of the sign of the derivative.

As is seen from the oscillogram, the maximum power setting after switching on the inverter is achieved after 8 - 9 cycles of the line voltage. Further acceleration of the transient process is inadvisable because of the possible negative effect of the inverter facility on the dynamic parameters of the plasma flow in the channel.

The system used for simultaneously regulating the electric parameters of the MHD generator on all the electrode pairs, on the basis of the derivative of the total electric power, is very effective for optimizing the electric load. This system has a significant stability margin with respect to self-oscillations, as distinct from a system of separate automatic optimization of the electric parameters on each electrode pair of the MHD generator.

The results of the tests of the combined operation of the multi-element converter facility with the U-02 MHD generator enable us to obtain the necessary reference data for producing a working model of an inverter

unit using thyristors for a large-scale installation with a MHD generator.

With a thin, comparatively hot ($T_w \approx 1{,}000°K$) boundary layer, the prebreakdown currents are large. After the beginning of breakdown, the intermodular voltage remains practically unchanged. /17

With a sufficiently thick boundary layer and a relatively low temperature or low admixture concentration in the layer, the character of the intermodular discharge is somewhat different.

In this case, the section corresponding to conditions of undeveloped breakdown is absent in the volt-ampere characteristic of the intermodular discharge: the first section of the characteristic, which is determined mainly by the leakage currents through the intermodular insulation, is abruptly terminated by the breakdown with a clearly expressed and sharply dropping characteristic. Thus, the prebreakdown currents are small ($\sim 0.1A$), but during the breakdown they increase by a factor of tens and hundreds, and the arcing voltage is substantially lower than the breakdown voltage. Such a discharge may occur in large MHD channels with "cold" modular walls.

For normal operation of the MHD channels, it is desirable that the intermodular voltage not exceed the arc triggering voltage. The undeveloped breakdown conditions also present no great danger, although current leakages in this case may affect the generator characteristics. Completed breakdown between the modules is entirely unacceptable since, when this occurs, currents which are dangerous to the structure may arise. In tests on the U-02 installation with a flow temperature of 2,800°K at the beginning of a channel having a boundary layer thickness $\delta \approx 1.8$ cm, the ignition voltage was around 40 V for the copper wall ($T_w = 450°K$). For a wall made of stainless steel ($T_w = 750°K$) it was around 20 V, and it increased for modules located beneath the flow to 100 - 120 V and 60 - 70 V, respectively, with an increase of δ by a factor of two. The voltage of the transition to a developed breakdown was approximately twice as large as the ignition voltage.

One may expect that in large MHD generators these numbers will be still higher, since the thicknesses of the boundary layer in them will be considerably larger. The numbers presented above also determine the permissible dimensions of the modules.

In tests on the U-02 installation, considerable attention was paid to investigating the behaviour of the insulation resistance of the modular wall structural elements during long-term operation. It turned out that in the first hours of operation, when the wall was in contact with the stream of combustion products with the K_2CO_3 admixture, the intermodular resistance and the resistance of the modules in respect to the ground decreased by approximately a factor of two, and after that they did not change for hundreds of hours (Figure 10). /18

STUDY OF A MHD GENERATOR

A large portion of the operations conducted on the U-02 installation were concerned with investigations connected with the MHD generator itself. The main purpose of the investigations was to study the effect of various factors (which depend both on the plasma flow parameters and also on the construction of the channel) on the MHD generator characteristics. Special attention was paid to studying the properties of the equipment during long-term operation.

When studying the MHD generator, a great deal of attention was paid to methodological problems and to problems of diagnosing the plasma flow. Spectral methods were incorporated in the U-02 installation and widely used for measuring the temperature of the flow and the admixture concentration in it. Probe methods were used for measuring the electron temperature and the conductivity and other factors [12]. The experimental investigation of the MHD generator was accompanied by a thorough theoretical analysis. During eight years of operation, about thirty MHD channels of various modifications were tested in it. In the overwhelming majority of cases, a Faraday generator with sectionalized electrodes was studied, but the

structural layout of the generator channel was very different.

Tests with the MHD generator on the U-02 installation were begun in 1965. In the first run, the power obtained from the MHD generator was only 200 watts, but already in the second run of this same channel the power was increased to 4 kW. The second channel, made with electrodes of silicon carbide and insulation of high aluminous concrete, resulted in a power of around 15 kW. Subsequent improvement of such a channel construction enabled the power of the MHD generator to be increased to approximately 40 kW toward the end of 1967. The operational results of this period were published in [1, 13].

In 1967 tests on the production of electric power on the U-02 installation were practically discontinued. Emphasis was shifted to studies of the individual units and structural elements of powerful MHD generators for long-term operation. Studies of localized characteristics of a MHD generator were conducted in parallel. Both "hot" and also "cold" channel construction variants were studied; however, the main attention was directed to an investigation of "cold" metal electrodes and metal, modular, insulated walls. This was determined by the fact that such designs were planned for the first channel variant of the U-25 [2].

The use of metals for MHD channels encounters definite difficulties. In the corrosive environment of combustion products, ordinary metals are able to operate only at moderate temperatures, three to five times lower than the temperature in the main body of the plasma flow. At such temperatures, the plasma conductivity is practically equal to zero and the current on the electrode can proceed only because of electric breakdown of the cold part of the boundary layer, with the formation of microarcs. The appearance of microarcs creates the danger of electrode erosion. However, this erosion is far from always being intense. It depends on the behaviour of the arcs, and in the final analysis is determined by the properties of the material and the electrode operating conditions.

An investigation of the microarc operating conditions was begun on the U-02 installation using flat electrodes mounted flush with the channel wall. The tests showed [14] that with a relatively thin, cold boundary layer, intensely luminous and slowly moving arcs arise on the electrode. These arcs burn on the edges where the field concentration occurs. Arcs frequently penetrate the gap between the electrode and adjacent insulator and cause noticeable erosion of the material. This led to the necessity of searching for new forms of cooled metal electrodes.

The first tests conducted with hemispherical electrodes protruding into the flow (Figure 7) showed that the above arcs are not observed on such electrodes. The number of arcs is considerably larger, but their lifetime and intensity are considerably smaller than on the flat electrodes. High-speed photography (up to 10^5 frames/sec) with synchronous oscillographic recording of the electric parameters enabled us to determine the main characteristics of the microarcs (number, dimensions, lifetime, etc.) as a function of the temperature and electrode material and its operating conditions.

Observations showed that, as distinct from flat electrodes where the concentration of the electric field at the electrode edges has a strong influence on the behaviour of the arcs, the behaviour of the microarcs on the electrodes protruding into the flow is determined mainly by the gas dynamics of the streamline flow of the electrode surface. After breakdown of the boundary layer, the flow carries away the arc trail and breakdown occurs between the trail and the electrode surface at a new spot. Since the region of breakdown is very narrow, the drift of the trail is determined not so much by the velocity of the advancing flow as by the velocity gradient at the wall. In the separation region of the boundary layer where the velocity gradient is close to zero, the arcs lose their mobility and are stabilized. They may move in this region as a result of large-scale fluctuations in the flow. /20

The effect of boundary layer separation on the behaviour of the arcs shows up especially clearly in tests with a wing-shaped electrode. With a

zero angle of attack, the flow around such an electrode is not separated. Only rapidly moving arcs are observed on its entire surface (except for the trailing edge). With an increase of the angle of attack, separation of the boundary layer takes place in the after zone of the electrode, and immediately slowly moving and intense arcs arise in the region of detached flow. By changing the angle of attack, one may observe how the boundary of the intense arc zone follows the change of the separated flow region boundary. This is shown schematically in Figure 8.

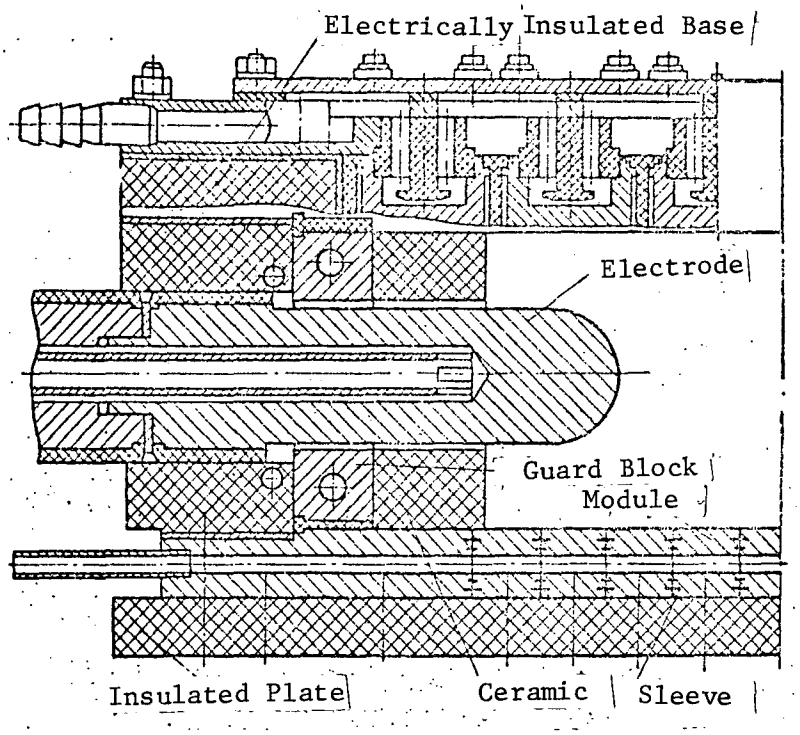


Figure 7. Section of the channel with extensible electrode.

The lifetime of the arc in the region of unseparated streamline flow of the electrode surface is up to 100 - 200 microseconds, and the lifetime of the arc in the region of boundary layer separation is 10 - 20 times larger (Figure 9, a, b). The /21 magnetic field does not qualitatively change the behaviour of the arcs, although it noticeably shortens their lifetime.

The behaviour of the microarcs directly affects the erosion being caused by them. Rapidly moving arcs do not cause substantial erosion of the electrode surface. Intense arcs burning in the region of boundary layer separation may cause appreciable erosion.

These results are clearly explained with a detailed investigation of the growth of cathode spots on a metal electrode in a motionless, cold gas.

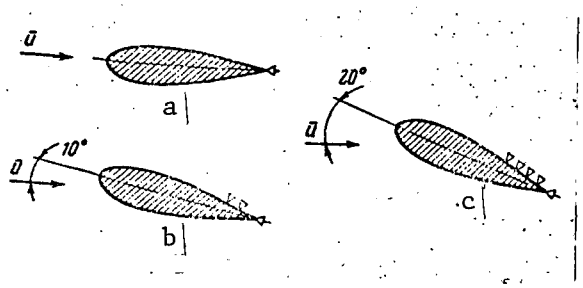
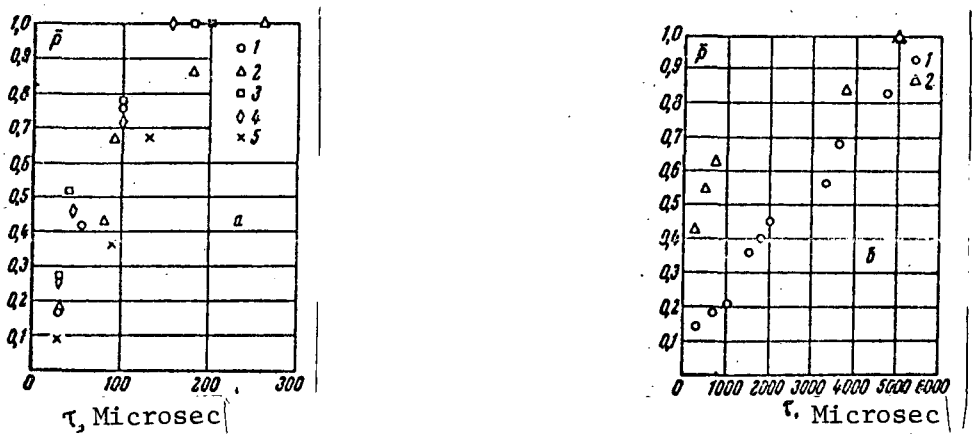


Figure 8. Effects of boundary layer separation on the burning region of intense arcs.

Intensification of the local heat removal from the cathode spot zone with a low average temperature of an electrode surface made of material with high thermal conductivity leads to a significant reduction in the dimensions of the cathode spots and to a sharp reduction of the erosion. The erosion of copper electrodes measured in long-term tests was ten times smaller than the erosion of electrodes made of stainless steel.



a) b)

Figure 9. Probability of the existence of arcs on the surface of a hemispherical electrode with a lifetime from 0 to τ:

a) the first half of the hemisphere with respect to the flow, Cu, T_w = 450°K, B = 0: J = I - 15a, 2 - 20a, 3 - 35a, 4 - 50a, 5 - 58a;

b) second half of the hemisphere, Cu, T_w = 850°K: 1 - I = 23a, B = 0; 2 - I = 19a, B = 1.7t1.

The admixture film settling from the flow onto the electrode surface has a large positive effect on the operation of a cold electrode. In the presence of such a film the rate of erosion of the electrode material

decreases by more than an order of magnitude.

Special tests of electrodes at a current of 100 - 120 A showed that the intensely cooled copper electrodes already existing possess a high electric erosion resistance and ensure operation of the MHD generator for hundreds of hours. At the present time, ways of further increasing the erosion resistance of electrodes are being planned and developed. /22

The present level of understanding the processes which determine the efficiency and lifetime of a cold electrode and also direct experiments on the model U-02 installation contribute to the successful solution of the cold electrode problem.

An investigation of the modular insulated wall was conducted simultaneously with the study of cold electrodes. The ohmic resistance of the intermodular insulation and the breakdown voltage between the modules along the plasma are important characteristics of a modular wall. A thorough study of these characteristics, as a function of the operating conditions and structural parameters of the modular wall, was conducted on the U-02 installation. The investigation was conducted with different structural designs of the modular wall, two variants of which are shown in Figure 7. The modules were made of copper, aluminum and stainless steel. Concrete, aluminum oxide Al_2O_3 deposited by means of plasma deposition, mica, dense ceramic and others were used as the insulation material in the gaps between the modules.

The tests which were conducted showed that porous materials (concrete, a sprayed-on layer of Al_2O_3, etc.) rapidly became saturated with the admixture and lost their insulation properties. The mica provides a fairly high insulation level and does not lose its properties during prolonged operation over many hundreds of hours, but if breakdown between the modules occurs the insulation properties of mica are not restored.

Dense aluminum oxide which is free of the defect inherent in mica showed the best insulation properties. With this, the resistance between the modules was established at a level on the order of 1 kohm and higher, which is entirely satisfactory for normal operation of a MHD generator.

With an increase in the potential difference between the modules, a discharge is triggered in the plasma near the module surface. The discharge first has the character of an undeveloped breakdown with an increasing volt-ampere characteristic. With sufficiently high potential differences, it changes into a clearly expressed breakdown. The triggering voltage U_1 and the breakdown voltage U_2 strongly depend on such factors as the plasma temperature, wall temperature, boundary layer thickness and admixture concentration. With a change of the boundary layer parameters, not only U_1 and U_2 change, but also the form of the volt-ampere characteristic itself changes.

The triggering voltage and breakdown voltage during prolonged operation of the channel remain unchanged (even a small increase of these parameters was observed) (see Figure 10). /23

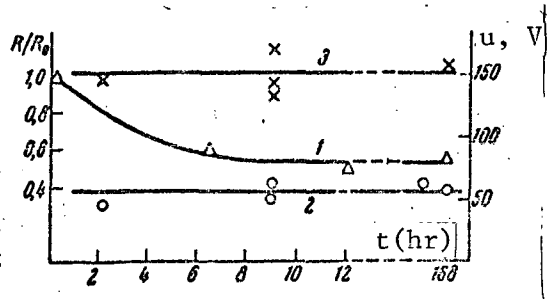


Figure 10. Change of the intermodular insulation parameters with prolonged operation of the channel:
1 - relative value of the module-ground resistance;
2 - triggering voltage;
3 - breakdown voltage.

The resulting data verifies the efficiency of a "cold" MHD channel, and are used in the operation of the Experimental Design Office of the Institute of Air Transport, the USSR Academy of Sciences.

Investigation and treatment also were conducted on the U-02 of a "hot" MHD channel with insulated walls lined with a high-temperature ceramic oxide and with ceramic electrodes of zirconium dioxide. This design can operate at a wall temperature up to 2,000°C, and provides a high efficiency for the MHD generator.

Ceramic electrodes of zirconium dioxide have an ionic surface which, at high currents, leads to destruction of the electrode. A great deal of work was done in searching for measures to combat this phenomenon. This work still is not finished, but already materials have been found which provide a current density of several amperes per square centimeter.

An investigation of the properties of a ceramic-lined insulated wall during prolonged operation showed that ceramic coatings do not have sufficient electric strength. Already at an induced voltage of 200 - 250 V, breakdown of the ceramic lining on a water-cooled metal base takes place. In order to eliminate this phenomenon, it is necessary to sectionalize the metal base. It is advisable also to sectionalize the ceramic coating since ceramic elements — even if not of very large dimensions — crack under the action of large heat fluxes. Porous ceramic is more durable. However such ceramic, even at relatively high surface temperatures (up to 1,400 - 1,500°C), is rapidly saturated by the condensing admixture which, when the thermal loop /24 is shut down, hydrates (with an increase of volume) and disintegrates the ceramic. It was experimentally established that this phenomenon is not observed with an increase of the temperature on the ceramic surface to 2,000 - 2,100°K.

Using the accumulated experience, a full-metric hot-design channel (channel XXV) was created with which combined tests, including tests for the production of electric power, were conducted on the U-02 installation (the 58th run).

The channel had a length of 3 m, a cross section of 200 X 64 mm^2 at the intake and 300 X 64 mm^2 at the outlet. The arrangement of the gas flow part of the channel is represented in Figure 11. Structurally channel XXV consisted of two parts. The first part, including the damping and 1^{st} operating section, was designed for a wall temperature of 2,000°C. The insulated wall of the first channel section was assembled from water-cooled copper modules with a ceramic lining made of magnesium oxide. The modules were made fast to a load-carrying plate of plastic. The electrode wall was

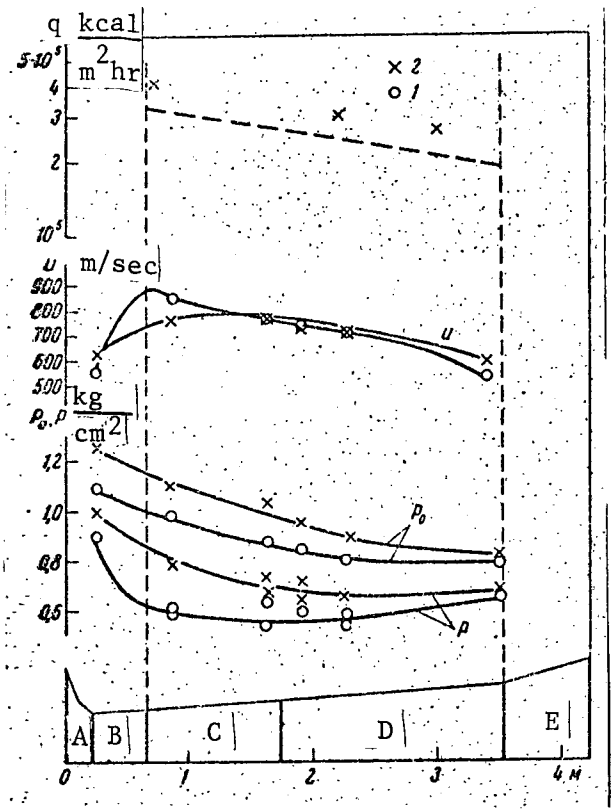


Figure 11. Distribution of the thermal and gas-dynamic characteristics along the length of channel XXV:
1 - without an electric load,
2 - under a load;

A - nozzle
B - cold section,
C & D - first and second operating sections,
E - exit cone.

built up of water-cooled electrode modules, to each of which two interelectrode insulators were soldered, and a ceramic electrode was arranged between the electrode modules. In the second section of the channel, electrodes of silicon carbide and an insulation made of highly aluminous concrete were used. The metal base of the insulated wall was cut into individual insulated sections with an area of 10 X 10 cm^2. This ensured high insulation reliability. Use of such a simplified construction of part of the channel enabled us to solve, with minimum costs, a number of important problems in studying the hydrodynamics and heat exchange of the MHD channel with a reliatively large MHD interaction, and also it enabled us to conduct complex tests of the installation loop with the removal of power from the MHD generator. The first operating section of the channel was designed for solving the second, no less important, problem of studying the electric characteristics of a hot-construction MHD channel during long-term operation.

The MHD generator had 52 electrode pairs. The first 12 pairs had reostats with stepped regulation for loads. The power from the remaining 40 pairs was removed by means of the inverter and delivered to a power line.

The tests of channel XXV continued for 28 calendar days with several interuptions for studying the effect of shutdowns, after prolonged operation with the admixture, on the properties and efficiency of the ceramic construction. During the tests, the power of the MHD generator was brought to 75 kW /25
with a combustion product flow rate of 0.95 kg/sec and a flow temperature at the intake to the channel of 2,760°K. The plasma conductivity at the intake to the channel reached σ_0 = 25 $ohm^{-1} \cdot m^{-1}$, and the Hall number was $\beta = 2.3$.

The distribution of the gas-dynamic and thermal parameters along the length of the channel for two of its operating conditions are shown in Figure 11. The increase of the retardation pressure drop which was observed in the tests with channel loading corresponds well with the removed power (0.15 atm with 75 kW). The distribution of the heat fluxes along the length of the channel corresponds to the calculated distribution, but the level of the heat fluxes was 30% higher than calculated. Evidently, this is explained by the effect of the wall roughness.

The distribution of the electric parameters along the length of the channel is presented in Figure 12. The voltage on the electrodes changed only slightly along the length. The small voltage jump between the 12^{th} and 13^{th} pairs is explained by the fact that the first 12 pairs were connected to an ohmic load, and the remaining pairs were connected to the inverter. The power removed from the electrode pairs in the first section changed slightly (by 20 - 30%). A maximum power of 2 kW is reached at half a meter from the inlet, and then the power drops to 1 kW at the end of the channel. The noticeable power dip at the beginning of the second section, evidently, is explained by overheating and fusing of the concrete coating, with the loss of insulation properties.

When making tests of channel XXV, a thorough investigation of the behaviour of the channel insulation during long-term operation also was /26
conducted. The effect of the channel operation duration with the admixture was studied, and also different operational situations which may affect the

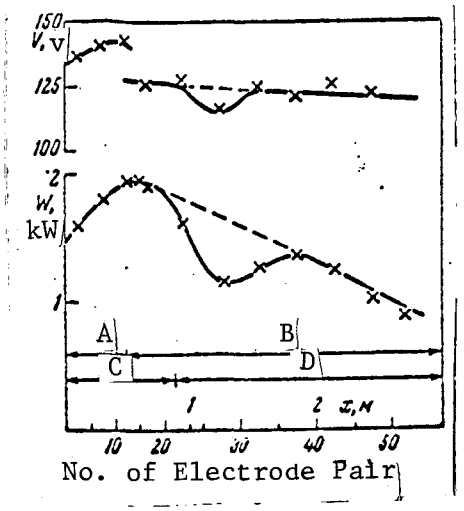


Figure 12. Distribution of the electric characteristics along the length of channel XXV:
A - the load is a resistance;
B - the load is the inverter;
C - section of ceramic electrodes made of Z_2O_2;
D - section of electrodes made from SiC.

insulation properties of the structure were investigated: a change in the conditions, a smooth shutdown of the loop, an abrupt (emergency) shutdown, the duration of the shutdown, and others. Measurements of the insulation resistance were conducted during the entire run (around a month) and showed that the insulation properties have a very high stability. During long shutdowns, the ceramic became saturated with moisture, and the resistance of its insulation deteriorated by a factor of several hundred. However, with a return to the operating conditions, the moisture evaporated and the insulation was rully restored.

The electrical characteristics of the first operating section were just as stable. The current and voltage on the pairs of the first section on the 28th day of the tests were practically the same as at the beginning of the tests.

The specific power removal in the first operating section reached an average of W = 3.3 MW/m^3, which is approximately 30% of the power for such s mall scales. This should be considered entirely satisfactory.

One may show that the ratio of the specific powers of a real generator and an ideal generator may be expressed by the following relationship:

$$\frac{W}{W_{ug}} = \frac{d_y \langle E_y \rangle}{0{,}25 \langle G \rangle \langle U B_T \rangle} = \frac{\left[1 - \frac{\Delta U}{\langle U B_T \rangle_h}\right]}{\langle G \rangle \left\langle \frac{1+B^2}{G} \right\rangle - \frac{\langle B_T^2 \rangle}{1+G_x}} \cdot \frac{\langle G \rangle}{G_0},$$

where $\bar{\sigma}_x = \bar{\sigma}^{\kappa}_{w} P / \langle \sigma \rangle F$ is the relative conductivity of the wall in the longitudinal direction, $\Delta U/h \langle UB \rangle$ is the relative potential drop adjacent to the electrode, and the symbol < > is the average taken across the channel. /27

The effect of various factors on the specific power of the generator associated with tests of channel XXV is shown in Table 2. As is seen from this Table, calculation gives a ratio of the powers of the real generator and an ideal generator equal to 0.33, which differs from the experimental value by 10%. From the analysis which was conducted, it is seen that almost all the possibilities of increasing the generator power were already used in the construction of the first operating section. The flow nonuniformity reduces the power most of all. However, it is not possible to reduce this nonuniformity, since the latter is connected with an increase of the limiting high temperature of the walls. At present, there are two real practical possibilities for increasing the specific power of the generator: improving the longitudional insulation of the electrode wall, and insulating the combustion chamber from the ground. As a result of these measures, one may expect that the specific power of the generator would noticeably increase and reach 40% of the ideal power. As calculations show, extending the construction of the first section, which was tested in a long-term run and fully justified itself, to the entire length of the MHD channel would enable the power of the MHD generator to be increased significantly.

Using the U-02 installation, it is suggested that in the future a broad complex of investigations be conducted — in particular, the study of supersonic flows and the improvement of electrode materials and the materials of the insulated walls. It is also important, using this installation, to perfect the appropriate elements and designs of MHD electric power stations.

TABLE 2

THE EFFECT OF VARIOUS FACTORS ON THE POWER REDUCTION OF A MHD GENERATOR

Factor influencing specific power	Quantity characterizing effect of these factors	Factor number	Factor considered when evaluating the power*									Experimental value
			1st	2nd	3rd	1st & 2nd	1st, 2nd & 3rd	1st 2nd 3rd & 4th	5th	1st 2nd 3rd 4th & 5th		
Transverse nonuniformity of the conductivity	$\Delta\sigma/\sigma_0 = 0.96$ $\langle\sigma'\rangle/\sigma_0 = 1.08$	1	+	-	-	+	+	+	-	+		+
Imperfect insulation in the channel	$\bar{\sigma}_x^{w} = 0.032$	2	-	+	-	+	+	+	-	+		+
Imperfect sectionalization of electrodes	$S_s/\sigma_x = 0.185$ $\sigma_x = 0.188$	3	-	-	+	-	+	+	-	+		+
Imperfect combustion chamber insulation	$\bar{\sigma}_x^{cc} = 0.101$	4	-	-	-	-	-	+	-	+		+
Potential drop adjacent to the electrode	$\Delta V = 20$ V $\Delta V/\langle uB\rangle h = 0.072$	5	-	-	-	-	-	-	+	+		+
Ratio of the optimum power to the power of an ideal MHD generator	$W/0.25\sigma_0\langle uB\rangle^2$		0.64	0.86	0.70	0.58	0.46	0.39	0.85	0.33		0.31

* (+) - the factor is considered
(-) - the factor is not taken into account

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